MINIATURE SCANNING CONFOCAL MICROSCOPE

Reference to Related Applications

The present application is a continuation in part of U.S. Patent Application Ser. No. 08/575,687, filed December 19, 1995.

Brief Description of the Invention

This invention relates generally to miniature confocal microscopes and more particularly to scanning confocal microscopes using micro-machined mirrors.

Background of the Invention

The standard optical microscope, used routinely in biology, medicine and semi-
10 conductor processing, is large. Typically, samples of tissue are observed *in vitro* after being mounted on a microscope slide. Such microscopes are not suitable for *in vivo* observations of the skin or internal organs of the human body; they are just too large. Consequently, there is a need for a small microscope which could be used for observations of melanomas of the skin, and the teeth and gums, and for endoscopy of cells inside
15 arteries and veins and organs of the body. Ultimately, if such a microscope could be mounted inside a hypodermic needle, it would be suitable for taking *in vivo* biopsies and for observing microscopic features of the body, such as the flow of blood and plasma in veins, arteries, and other vessels of the body, the fluid in tear ducts, and the general condition of small vessels. Although we have described biological applications of a
20 miniature microscope, the miniature microscope of the present invention can be used in endoscopes passed through small pipes, and for use *in-situ* observation during processing of semiconductors and other materials.

The present tendency is to carry out clinical procedures with small tools mounted in catheters, to make internal observations inside vessels with fiber optic devices, and to
25 carry out operations using laser and fiber-optic techniques. Much less damage is done to the body than with older surgical methods by using such procedures. Observations of what

is being done on a microscopic scale would be helpful, since the best resolution that presently can be obtained with endoscopes is of the order of 10-20 μm. Another example is the observation of cancer cells in the uterus, where it is extremely painful to carry out biopsies. An *in vivo* imaging technique for this purpose which leaves the tissue intact

5   would be a considerable improvement over present practice.

Several fiber optic microscopes have been suggested in the past, but either they are too bulky or too slow, so that the frame time is of the order of several seconds, or the definition is very poor[1-6]. Thus, these microscopes are not suitable for *in vivo* real-time imaging at the microscopic level.

10   We reported a vibrating fiber microscope in a recent paper[7]. A Fresnel lens made by photolithographic means was mounted on the end of a vibrating glass rod approximately 0.8 mm square. The lens was illuminated from an optical fiber glued to the other end of the rod, and formed a spot of the order of 1.8 μm in diameter at an approximate distance of 1 mm from the lens. Light reflected from the object being observed was passed back

15   through the fiber and lens to a detector. The signal from the detector, after suitable processing, was displayed through an image converter as a video image. The rectangular-shaped rod was vibrated by electrostatic fields, applied between it and an outer tube, at its slightly different mechanical resonant frequencies in the x and y directions. Hence, the focused spot from the lens formed a raster pattern (a Lissajous figure). The vibration

20   frequencies were of the order of 8 kHz, and a single frame of the image took about 1/20 second to form. The resolution was about 2 μm. This microscope suffered from the disadvantage that the vibrating rod needed support from a rigid and massive structure, which made the supporting structure large and unsuitable for use in the body.

Objects and Summary of the Invention

25   It is an object of this invention to provide a micro-machined miniature scanning optical microscope.

It is another object of the invention to provide a miniature scanning optical microscope using micro-machined, electrostatically actuated scanning mirrors.

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It is still another object of the invention to provide a miniature scanning optical microscope using micro-machined, electrostatically actuated scanning mirrors and a micro-machined binary lens.

There is provided a scanning optical microscope which incorporates electrostatically actuated scanning mirrors disposed between a single-mode optical fiber light source/ detector and a focusing objective lens.

Brief Description of the Drawings

The foregoing and other objects of the invention will be more fully understood from the following description read in connection with the accompanying drawings, of which:

Figure 1 is a perspective view of a miniature confocal scanning microscope in accordance with the invention;

Figure 2 is an exploded view showing the parts of the microscope of Figure 1;

Figure 3 is a sectional view taken along the line 3-3 of Figure 1;

Figure 4 is a sectional view taken along the line 4-4 of Figure 1;

Figure 5 is a sectional view taken along the line 5-5 of Figure 1;

Figure 6 shows the zone plate line schematically illustrated in Figures 1 and 2;

Figure 7 shows the angles employed in the design of an off-axis zone plate lens;

Figure 8 shows the optical fiber illumination/detection configuration;

Figure 9 shows an open-loop electronic drive circuit associated with the scanning mirrors and the signal processing circuit

Figure 10 shows a closed-loop electronic drive circuit associated with the scanning mirrors and the signal processing circuit;

Figure 11 shows an image of chrome lines on a glass substrate taken with a microscope in accordance with the invention;

Figure 12 shows another image of chrome lines on a glass substrate taken with a microscope in accordance with the invention;

Figure 13 shows an image of a silicon test structure taken with a microscope in accordance with the invention; and

Figure 14 shows an image of red blood cells taken with a microscope in accordance with the invention.

Figure 15 is an exploded view of another embodiment of the scanning mirrors and substrates shown in Figures 1-4.

Figure 16 is a partial sectional view of one of the scanning mirrors shown in Figure 15.

5   Figure 17 is a top plan view of the mirror shown in Figure 16.

Figure 18 is a sectional view of a scanning microscope incorporating a detector.

Figure 19a is an enlarged view of the portion 19-19 of Figure 18.

Figure 19b is an end view of the single mode optical fiber.

Figure 20 is a sectional view of a scanning microscope head showing a refractive

10   focusing lens.

Figure 21 is a sectional view of a scanning microscope employing a biaxial scanning mirror.

Figure 22 is a top plan view of the biaxial scanning mirror of Figure 21.

Figure 23 is a sectional view of the biaxial scanning mirror of Figure 22.

15   Figure 24 shows the frequency response of both the inner plate and the combined inner plate and outer frame.

Figure 25 shows the frequency response for the inner plate for a range of values of common mode dc bias voltage.

Figure 26 shows the angular deflections of mirror and frame as a function of dc bias

20   voltage.

Figure 27 shows a chrome bar target image by a microfabricated confocal microscope in accordance with Figure 21.

Figure 28 shows a miniature confocal scanning microscope mounted in a hypodermic tubing.

25   Description of the Preferred Embodiment

A miniature scanning confocal microscope in accordance with the invention is illustrated in the perspective view of Figure 1, the exploded view of Figure 2 and the sectional views of Figures 3-5. The microscope includes a silicon substrate 11, a bonded silicon plate 12, a single mode optical fiber 13, a silicon spacer 14 and a fused silica lens

30   plate 16 bonded to the silicon spacer 14. The plate 12 includes a pair of micro-machined

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scanning mirrors 17, 18 disposed between the single mode optical fiber 13 and a miniature objective lens 19 formed in the silica lens plate 16. The silicon spacer comprises <100> silicon which is etched to form an opening 21 which forms a <111> face 22. Referring to Figure 3, the light beam 23 from the fiber 13 is first reflected from the etched <111> face 22 onto the first scanning mirror 17, then from a metallized mirror 24 on the lens plate 16 back to the second scanning mirror 18. The light beam is then reflected from the second scanning mirror 18 and passes through an off-axis zone plate objective lens 19 etched into the fused silica lens plate 16. The lens images the output from the fiber to a point 26 on the sample plane. As the mirrors rotate, this point is scanned through the field of view. Light reflected back from the sample is re-imaged by the lens 19, back along the same path to the fiber, and is detected and processed to create an image. Since the fiber behaves like a small pinhole, the device is a confocal microscope with the range and transverse resolution to be expected from a confocal scanning-optical microscope.

The mirror scanners are fabricated using silicon micro-machining techniques. Micro-machined torsional mirrors for use in scanners and spatial light modulators have been reported by numerous authors.[8-14] The rotational axes of the two mirrors are orthogonal, so that one mirror scans the light beam in the x-dimension and the other mirror scans it in the y-dimension. As will be presently described, the mirrors 17, 18 are electrostatically rotated.

The silicon substrate 11 is masked and etched to form spaced wells 28, 29 below the mirrors 17, 18 whereby the mirrors can rotate. The substrate is masked and impurities are implanted into the substrate to form conductive regions. More particularly, two conductive regions 31, 32 are formed at the bottom of well 28 and two conductive regions 33, 34 are formed at the bottom of the well 29. These regions are connected to ion-implanted contact regions 36, 37 and 38, 39 by ion-implanted leads 41, 42 and 43, 44. A bonding thermal oxide layer 46 is formed on the surface. A silicon nitride cap is formed over the oxide in the wells 28, 29 to provide insulation during a subsequent metallization step.

The silicon plate 12 is bonded to the substrate via an oxide layer on the plate and the substrate oxide 46. A silicon nitride layer 47 is formed on the plate 12 and by suitable

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masking and etching, windows 51, 52 and 53, 54 are formed to expose the contact regions 36, 37 and 38, 39. The mirrors 17, 18 are defined by etching the slots 56 leaving silicon nitride strips 57, which serve as hinges. The etching removes the silicon from beneath the hinges while leaving the silicon under the mirror surfaces to provide a rigid mirror. After 5 the mirrors have been defined, a conductive layer is deposited on the top of the silicon plate to provide, on the surface of the mirrors, a reflective surface and one plate of a capacitor which cooperates with the conductive regions 31, 32 and 33, 34 to provide electrostatic forces which cause the mirrors to rotate at the hinges. Actuation of the mirrors is accomplished by applying voltages between the conductive film on the surface 10 of the mirror and the individual implanted regions 31, 32 and 33, 34. The conductive film also covers the implanted contact regions 36, 37 and 38, 39. The film at the upper surface of the plate is not in contact with the film at the contact areas.

The off-axis zone plate lens, Fig. 6, is fabricated using electron beam lithographic pattern transfer and anisotropic reactive ion etching. The angles at which the light beam 15 enters and exits the lens are specifically designed so that the beam emitted from the lens is well focused throughout the field of view, with no second order aberrations. The local structure of the lens grating has itself been optimized to increase the efficiency of the lens relative to a similar lens designed for on-axis imaging.

The quality of the image formed by the microscope is governed by the design of the 20 lens. Traditional microscope objectives have many glass elements all of which are combined to reduce the aberration of the image to a minimum. For this invention, one benefits from the use of a very simple, single element objective. Because a laser source illumination at a single wavelength of light is used, one can use a diffractive lens rather than the more usual refractive type. This is a distinct advantage from a manufacturing 25 point of view since a diffractive lens can be made lithographically with tight control over the pertinent design parameters. One gives up, however, the expectation of performing aberration-free imaging when one chooses to implement the microscope with a single diffractive lens element.

The aberrations of axially symmetric grating lenses are well known. For this 30 application, one desires high resolution and, therefore, high numerical aperture in the

objective lens. The primary aberration (so-called third order aberration) that limits numerical aperture in an axially symmetric grating lens with the stop at the lens is coma.

With the zigzag optical path used for the microscope, one requires a lens that is not axially symmetric, but is designed to create an image from a beam of light that is incident at an angle from the lens normal. In general, such an off-axis lens will suffer from a more serious second order aberration called linear astigmatism. It has been discovered, however, that if the angles of incidence of the object beam and the image beam are chosen properly then the second order astigmatism disappears and imaging is again governed by third order coma. The constraint on the angles is that

$$\sin(\alpha_1)/r_1 = \sin(\alpha_2)/r_2 \tag{1}$$

where the angles α_1, α_2, r_1 and r_2 are defined in Figure 7.

The phase function of this lens is such that the points in the center of the field of view, P_1 and P_2 are perfect images of one another.

When the microscope is constructed with regard to this constraint on the angles made by the incoming and exiting beams with the normal to the lens plane, then the imaging aberrations of the off-axis lens are quite similar to the aberrations of the more familiar, axially symmetric lens. Any significant deviation from this relationship would result in an instrument with extremely poor performance, and therefore the geometric relationship described above is paramount to the operation of the microscope. On the other hand, the fact that there exists a situation favorable to off-axis imaging enables one to implement the microscope with a zigzag optical path, keeping the overall dimensions very small and the design simple.

Note finally from the figure that the object and image planes are normal to the direction the beam of light is traveling. This is important for a reflection microscope, since the lens must collect the light reflected from the sample. If the sample plane was tilted with respect to the incoming beam, then the reflected light would not retrace its path back into the lens.

The single mode optical fiber illumination/detection system is shown in Figure 8. A light source 61, such as a 3 mw helium-neon laser at 632.8 nm supplies light to one end of a single-mode optical fiber 62 which is used as a flexible conduit to deliver light to the fiber 13 which serves as the point source and detector for confocal operation

5 of the microscope. The single lens focuses the light from the fiber onto the sample and collects the back-scattered light. A directional coupler 63 directs the reflected light from the sample onto photodetector 64 to provide an output signal 66.

The scanning microscope electronic interface is simple in principle. Referring to Figures 9 and 10, each scanning mirror is driven by two symmetrically placed

10 electrodes 31, 32 and 33, 34, one on either side of the rotational axis. Application of a voltage between the electrode and the mirror plate results in an attractive electrostatic force proportional to the square of the magnitude of the voltage. To tilt the mirror one way or the other, a voltage is applied to one electrode at a time causing the mirror to deflect toward that electrode. For oscillatory motion in the x and y direction, a

15 sinusoidal drive voltage 67 is applied to one of the electrodes 31, 33 with a DC bias sufficient to keep the voltage always positive. The opposing electrodes 32, 34 receive a drive voltage 68 with the opposite phase, so that as one side of an electrode sees the maximum voltage the other side sees zero voltage resulting in a net torsional force at the mirror. The frequency of the drive signal may be adjusted to cause the mirror to

20 oscillate at its natural resonance or off resonance. Near resonance, the motion of the mirror will be phase shifted relative to the drive voltage waveform. In order to form an image from the detected light reflected from the sample, it is necessary to know the precise position of the mirror. A scan converter 69 is used for this purpose, which takes as its input the drive signals and the detected optical signal from the fiber, and

25 produces as its output a raster scanned image suitable to display on a monitor 71 or for capture on a computer 72.

There are two possible control schemes. The simplest is *open loop control*, Figure 9, where it is assumed that the kinetic response to the mirrors is known well enough that one only need to monitor the drive voltage in order to predict the mirror

30 position. Then the scan converter maps the intensity of the detected optical signal to

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the calculated position of the beam. The other scheme is *closed loop control*, Figure

10, where the position of the mirrors is independently monitored and this information is

used in a feedback scheme that attempts to lock the motion of the mirrors to the drive

voltage waveform. One of the simplest ways to monitor the position of the mirror is to

5   measure the capacitance between the mirror plate and the drive electrodes. This

capacitance will vary with the angular position of the mirror, so that monitoring the

capacitance fluctuation provides a direct measure of the mirror position. With closed

loop control, the control loop is capable of making the mirror motion exactly follow the

drive voltage, so that the scan converter may use the x and y drive signals directly to

10   map the intensity to the proper position of the beam, without any specific knowledge of

the mirror kinetics.

A microscope was constructed which was 6 mm long, 2.5 mm wide and 1 mm

high. The scanning mirror 17 was 300 μm by 360 μm and the scanning mirror 18 was

500 μm by 600 μm. The single mode optical fiber 13 was 125 μm in diameter.

15   The microscope was operated to provide both raster-scan and lissajous-scan

images. In the first example, the microscope was used to scan a glass substrate

provided with chrome lines 2 μm wide on 4 μm centers and a 5 μm line. The mirror

17 was scanned at a frequency of 2.71 kHz with approximately 20V peak-to-peak

sinusoidal voltage. The mirror 18 was driven at a frequency of 5 Hz with

20   approximately 25 peak-to-peak sinusoidal voltage. The field of view was 30 x 24 μm.

The resulting raster-scan image is shown in Figure 11, which has 271 lines/frame at a

frame rate of 5 Hz. The 2 μm lines are shown at 76 and the 5 μm line is shown at 77.

In the second example, the microscope was used to scan a glass substrate with

chrome lines 2 μm wide on 4 μm centers and 5 μm lines on 10 μm centers. The mirror

25   17 was scanned at a frequency of 4.3 kHz with approximately 30V peak-to-peak sinu-

soidal voltage. The mirror 18 was driven at a frequency of 1.07 kHz with

approximately 25V peak-to-peak sinusoidal voltage. The field of view was about 80

μm x 60 μm. The resulting lissajous-scan image is shown in Figure 12. The frame

rate was 8 Hz with 268 lines/frame. The 2 μm and 5 μm lines are shown at 78 and 79.

In another example, the microscope was used to scan an etched silicon test structure having U-shaped trenches. The mirror 17 was scanned at a frequency of 4.3 kHz with 30V peak-to-peak sinusoidal voltage, giving a field of view of 80 μm x 60 μm. The resulting Lissajous-scan image is shown in Figure 13. The trenches are

5   shown at 81. The frame rate was 8 Hz with 268 lines/frame.

In a fourth example, the microscope was used to scan red blood cells on a glass slide. The mirror 17 was scanned at a frequency of 4.3 kHz with a 30V peak-to-peak sinusoidal drive voltage. The mirror 18 was driven at a frequency of 1.07 kHz with a 15V peak-to-peak drive voltage. The field of view was 40 μm x 60 μm. The resulting

10   Lissajous-scan image is shown in Figure 14. The red cells are shown at 82. The frame rate was 8 Hz with 268 lines/frame.

Figures 15-17 show another embodiment of electrostatically rotated scanning mirrors for miniature scanning confocal microscope in accordance with the present invention. A bonded wafer technique was employed to fabricate the electrostatically

15   deflected mirror assembly. A substrate 11a was prepared with a clearance well 86. Then a second silicon wafer 12a was bonded to the substrate. The silicon wafer was micromachined to form the mirror plates. The mirrors 17a, 18a, each consist of a silicon plate. Note, silicon plate 89 is shown in Figure 16, supported by torsion hinges 91, 92, and 93, 94. The hinges are made of a low stress silicon nitride. In one

20   example, the mirrors were 500 μm by 500 μm and 25 μm thick. The mirrors were separated from the silicon substrate 12a by a gap of approximately 25 μm. The mirrors were actuated by electrostatic attractive forces when a voltage was applied across the gap between reflecting metal electrodes 96, 97 and 98, 99 formed on top of the top surface of the silicon plates. The metal electrodes serve both as the reflective mirror

25   surface and as a drive electrode for actuation of the mirror on its hinges. Connection to the two sets of electrodes is made by leads 101, 102, 103, 104 formed as a thin film on the top surface of the silicon nitride layer.

The starting material for the substrate 11a was [100] p-type silicon, 0.1 Ω-cm. The substrate was prepared with a thin thermal oxide layer for bonding and then the

30   well 86 was patterned and etched into the substrate to the desired depth using reactive

ion etching. The starting material for the top plate wafer 12a was [111] p-type silicon, 5000 Ω-cm. It was also prepared with a thermal oxide layer and then bonded to the substrate 11a using a fusion bonding technique. The top plate was ground and polished to the desired final plate thickness of 25 μm. A 1000 Å thermal oxide layer was

5   deposited followed by a 1 μm film 105 of low stress silicon nitride for the hinge material. Next, contact openings were patterned and etched through the silicon nitride and the underlying oxide, followed by a phosphorus implant and anneal to define n+ regions 106, 107 forming pn junctions between the metal electrodes 98, 99 and the p-type plate. Similar implant regions and pn junctions (not shown) were formed between

10   the electrodes 96, 97 and the underlying p-type plate. The mirror outlines and hinges were then patterned and etched into the nitride layer, followed by deposition and patterning of the chrome-gold reflective electrodes. Finally, the silicon was etched anisotropically around the perimeter of the mirrors and beneath the hinges using a mixture of hydrofluoric, nitric and acetic acids (HNA), and the structure was released

15   by etching the underlying bonding oxide. The complete substructure is shown in Figures 15-17.

Using a silicon plate for the mirror, insures a rigid, optically flat surface that did not distort during scanning and at a thickness of 25 μm. It suffered minimal bowing from the intrinsic stress in the silicon nitride film. To actuate the plate, it is necessary

20   to establish a voltage across the gap between the plate and the substrate. In order to accomplish this using electrodes deposited on the top of the plate, the silicon support or wafer must be depleted of free carriers beneath the driving electrode. To assure depletion through the 25 μm thick plate, high resistivity silicon was used for the plate. The metal electrodes as described were electrically connected to the silicon plate

25   through a pn junction as illustrated in Figures 16. When a voltage difference was applied between the driving electrodes, the pn junction under the more positive electrode was reversed biased and the full region beneath the electrode was depleted to a depth W given approximately by the formula

$$W = (2\varepsilon(V - V_{bi})/qn_a)^{1}/_{2} \qquad\qquad (2)$$

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where ϵ is the permitivity of silicon, V is the applied voltage, V_{bi} is the built in junction potential, q is the electron charge and n_a is the acceptor concentration for p-type silicon.

With selected resistivity for the mirror plates, the p-type silicon resistivity corresponds to an acceptor concentration of $n_a = 2.6 \times 10^{12}$ cm^{-3}. Using the above

5 relationship, the plate will be fully depleted for a differential voltage between the electrodes of approximately 2.5 volts. The electrostatically deflected mirror assembly describe in connection with Figures 15-17 simplifies the construction of a scanning mirror arrangement by eliminating the need for implanted regions and simplifies the electrical connections for application of deflection voltages. In other respects, the

10 microscope operates in a manner previously described.

Rather than employing the fiber coupler 63 shown in Figure 8, the confocal scanning microscope may employ a single mode optical fiber solely for the transmission of light to the scanning mirrors. A diode detector 64 may be placed adjacent to the inclined end 110 of the single mode fiber and a thin metal film dot beamsplitter 111 can

15 be formed on the inclined end 110 of the fiber, Figures 18 and 19. The beam reflected from the object will then strike the inclined face of the fiber and be reflected downward by the metal beamsplitter to the diode 64 which will provide an output signal 66. By making the metal film the diameter of the fiber core, one will only get a signal from the diode 64 when the beam is focused on the core. The system acts as a confocal

20 microscope. To eliminate reflectivity from the cladding surrounding the core of the fiber, the fiber may be provided with an anti-reflection coating (not shown).

The off-axis diffractive lens, Figure 6, can be replaced by a refractive lens in the form of a glass sphere 112, Figure 20, formed from a material with a high index of refraction and small dispersion such as zirconia, where n=2.2 to minimize aberrations.

25 The sphere would be in the order of 1 mm diameter and held by lens holder 113. Other configurations could incorporate a tilted hemisphere which would give even less aberration. The surface of the scan mirrors can be modified to include a reflective diffractive lens (not shown) or a reflective phase plate (not shown). The purpose of such modification could be to replace the fixed lens or to function in concert with the

30 fixed lens to provide aberration compensation.

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We have found that the microscope can be shortened by replacing the two mirror arrangement with a biaxial mirror arrangement such as that illustrated in Figures 21-23. In Figure 21, like reference numerals have been applied to the same pats as described with reference to Figures 1-6. The assembly is simplified in that it requires only one

5   metallized mirror for deflecting the beam in both the x and y direction. The system is made by mounting the mirror 116 on hinges 117, 118 to a frame 121 supported by hinges 122, 123 from the plate 12a. The mirror consists of a silicon plate 126 supported by torsion hinges 117, 118 made of low stress silicon nitride. Frame and mirror plate are separated from the silicon substrate by a gap of approximately 25 μm.

10   The mirrors are actuated by the electrostatic attractive forces when a voltage is applied across the gap. Two metal electrodes, 136, 137 serves both as a reflective mirror surface and as a drive electrodes for actuation of the mirror on the hinges 117, 118. Two additional electrodes 138, 139 on the frame are used for actuation of the frame in an orthogonal direction. Connection to both sets of electrodes are made by wires 141,

15   142, 143, 144 bonded to the electrodes and to thin film leads 146, 147, 148, 149 formed on the surface of the nitride film to be described. As before, the substrate was highly doped p-type silicon, 0.1 Ω-cm. The substrate was prepared with a thin thermal oxide layer for bonding and then the well 151 was patterned and etched into the substrate to the desired depth, 25 μm, using reactive etching. The starting material for

20   the top plate was a substantially intrinsic p-type silicon, 5000 Ω-cm. It was also prepared with a thermal oxide and bonded to the substrate using a fusion bonding technique. The top plate was then ground and polished to the desired final plate thickness. A 1000 Å thermal oxide layer was deposited followed by a 1 μm of low stress silicon nitride for the hinge material. Next the contact openings for the pn

25   junction were patterned and etched to the silicon nitride and underlying oxide followed by phosphorus implant anneal to define an n+ region beneath the contacts. The mirror outlines and hinges were patterned and etched into silicon nitride followed by deposition and patterning of chrome-gold electrodes. Finally, the silicon was etched anisotropically around the perimeter of the mirror and underneath the hinges using a

mixture of hydrofluoric, nitric and acetic acids and the structure was released. The completed structure is shown in the Figures 22 and 23.

We have characterized the scan mirror in terms of their frequency response, and angular displacement as a function of applied drive signal. The dynamic behavior of

5   the mirrors can be described, in the absence of damping, using the second order equation of motion given by

$$T = I_p \ddot{\Theta} + \frac{2KG}{l}\Theta \tag{3}$$

where I_p is the moment of inertia of either the plate or the plate and frame combined for motion about the inner and outer hinge axes, respectively. For the motion of the inner plate with dimension c along the hinge axis and b transverse to the axis, we have

10   $I_p = pcb^3t/12$ where t is the plate thickness and p is the density of silicon (2.32 g/cm^3). The restoring torque of the nitride membrane hinges is $\Theta 2KG/l$, where l is the hinge length, and G is the elastic modulus of the membrane in shear, which is related to the tensile elastic modulus E (Young's modulus) by Poisson's ratio v according to $G = E/2(1+v)$. The factor K is related to the polar moment of inertia of the nitride

15   support arm. For a rectangular cross section, K is give by [10]

$$K = a\delta^3 \left[\frac{1}{3} - 0.21\frac{\delta}{a}\left(1 - \frac{\delta^4}{12a^4}\right)\right] \tag{4}$$

where a is the width of the hinge and δ is the thickness of the nitride layer.

The torque on the plate is given by

$$T = \int F(x)x \mathrm{d}A \tag{5}$$

where x is assumed to be in the direction transverse to the hinge axis, and $F(x)$ is the force per unit area, which can be written, for the range θ of through which the biaxial mirror can rotate, as

$$F(x) = \frac{1}{2}\frac{\epsilon_0 V^2}{(s_0 - x\Theta)^2}.$$ (6)

In this equation θ is the angle separation between the plate and the substrate.

5   Because the electrostatic forces are a function of the square of the applied voltage, it is often desirable to operate the device with a dc bias on the electrodes, so that the voltage is unipolar and the mirror response is at the same frequency as the drive voltage rather than twice that frequency. The presence of a dc bias will, however, alter the resonant frequency of the mirror. To see this effect, consider the behavior of the

10   inner plate. One can let the voltage across the gap $V -_{dc}$ be constant across the plate, and then expand the expression for the torque as a function of θ. For a small angular displacements, this becomes

$$T_{dc} = \frac{1}{12}\frac{V_{dc}^2\epsilon_0 b^3 c}{s_0^3}\Theta + \mathcal{O}(3)$$ (7)

where O(3) means terms of order 3 or higher in θ. Now the equation of motion becomes

$$\frac{1}{12}\frac{V_{dc}^2\epsilon_0 b^3 c}{s_0^3}\Theta = I_p\ddot{\Theta} + \frac{2KG}{l}\Theta.$$ (8)

15   This structure will have a resonant frequency given by

$$\omega_0 = \left[\frac{2KG}{lI_p} - \frac{V_{dc}^2\epsilon_0}{\rho t s_0^3}\right]^{1/2}.$$ (9)

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Increasing the DC bias voltage has the effect of lowering the resonant frequency of the mirror plate.

Figure 24 shows the frequency response of both the inner plate, and the combined inner plate and outer frame, for a particular mirror device. This data

5   corresponds to a square mirror plat measuring 500 μm along a side and 25 μm thick. The hinge for the plate was 1 μm thick, 20 μm wide and 25 μm long. The outer frame is also square, with inner dimension 520 μm and outer dimension 720 μm. The hinge for the frame was 1 μm thick, 16 μm wide and 50 μm long.

Frequency data were measured for the inner plate of this particular mirror for a

10   range of values of common mode dc bias voltage. In Figure 25, the dependence of resonant frequency upon the bias voltage, which is described by Equation 9, is illustrated by plotting the square of the frequency vs. The square of the bias voltage. For voltages small enough that the plate-substrate separation $\delta\theta$ is constant, this relationship is linear. The y intercept of the curve is equal to the spring constant of the

15   hinges divided by the moment of inertia of the plate. We can use this number to calculate the shear modulus G for the silicon nitride hinges. For this device, we find that $G = 6.5 \times 10^{10}$ [N/m].

For real time, video rate scanning it is desirable to operate with a line scan frequency in the range of 8 to 10 kHz, and possibly higher for some applications. The

20   highest resonant frequency we have measured with the current mirrors is 2.7 kHz. By increasing the hinge thickness to increase the spring constant, and decreasing the plate thickness to reduce the moment of inertia, this mirror architecture should easily scale to provide resonant line scanning at 10 kHz with a plate that measures 500 μm x 500 μm.

For raster type scanning using the biaxial mirror, the outer plate is typically

25   operated well below resonance, at a few Hertz to tens of Hertz. In this frequency range, we can approximate $\theta \approx 0$, and the angular displacement of the mirror is governed by the static equation

$$T = \frac{2KG}{l}\Theta. \tag{10}$$

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We have measured the static displacement of the mirror and frame as a function of a dc voltage applied to one of the frame electrodes, with the center plate and the other frame electrodes all grounded. The results are plotted in Figure 26. Also plotted in the figure is the theoretically predicted deflection which is calculated by evaluating the integral of

5   Equation 5 over one side of the outer frame. We then use the following expression for the torque with the torque T given by the relation

$$T = \frac{\epsilon_0 V^2}{2\Theta^2} \left[c_2 \left(\ln\left(1 - \frac{\Theta b_2}{2 s_0}\right) + \frac{\Theta b_2/2 s_0}{1 - \Theta b_2/2 s_0} \right) - c_1 \left(\ln\left(1 - \frac{\Theta b_1}{2 s_0}\right) + \frac{\Theta b_1/2 s_0}{1 - \Theta b_1/2 s_0} \right) \right]$$

(11)

where $b_1 = c_1 = 520\ \mu$m are the frame inside dimensions and $b_2 = c_2 = 720\ \mu$m are the frame outside dimensions. The only material parameter appearing in Equation 10 is the elastic shear modulus G. Using the number for G calculated from the frequency

10   response data yields an excellent agreement between the theoretically predicted and measured static deflection as a function of applied drive voltage.

We have used the biaxial silicon torsional mirror as the scanning element in a microfabricated fiber confocal optical microscope[6,7]. The device, which is illustrated in Figure 21, consists of a substrate wafer with the scan mirror fabricated on its surface, a

15   second silicon wafer with a anisotropically etched cavity in which the light beam propagates, and a top plate made of fused silica which contains the grating lens used to focus the light beam onto the sample being imaged. The light emerging from an angle polished single mode optical fiber is reflected from a stationary mirror on the etched cavity face before it encounters the center plate of the biaxial scan mirror. The

20   reflected light from the scan mirror passes through the objective lens and is focused to a spot on the sample. Light reflected from the sample is collected by the lens and retraces its path back into the fiber, where it is detected to generate a signal proportional to the sample reflectivity. Actuation of the scan mirror causes the focused spot to raster across the sample, and an image is formed point by point.

Figure 27 shows an image of a test pattern of chrome lines on a glass substrate that was obtained with the microfabricated microscope and the biaxial scan mirror. The wider lines are 5 μm wide on a 10 μm period, and the narrower lines are 2 μm wide on a 4 μm period. The numerical aperture of the lens is 0.25, and the focused spot is 1

5   μm fwhm. The field of view for this image is 60 μm X 60 μm (one division on the grid is 10 μm), corresponding to $\pm 1.5°$ angular displacement of the scan mirror. This image was taken using a triangular frame scan at 10 Hz and a sinusoidal line scan at 1.8 kHz, without benefit of retrace blanking for either the line scan or the frame scan.

Referring to Figure 28, a micromachined microscope 155 in accordance with the

10   present invention is shown mounted on a PZT Bimorph 156 inside a hypodermic needle tubing 157 having a window 158. By applying suitable voltages to the bimorph, the microscope 155 can be deflected to focus at various sample planes 159. The hypodermic tubing is shown mounted to a cable 161 which houses the optical fiber, the leads for driving the scan mirror electrodes, and receiving signals from the detector 64

15   from the scanning head. The micromachined confocal microscope can also be mounted for use in dentistry, dermatology, etc.

Although a specific embodiment of the invention has been provided, modifications can be made without departing from the invention. For example, the mirrors may be cantilevered or supported on a single post. There has been provided a

20   miniature scanning confocal microscope making use of micro-machined scanning mirrors and parts.

The foregoing description of specific embodiments of the invention have been presented for the purpose of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, and obviously many

25   modifications, embodiments, and variations are possible in light of the above teaching. It is intended that the scope of the invention be defined by the claims appended hereto and their equivalents.

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